Ecological and economic assessment of the effectiveness of implementing bioenergy technologies in the conditions of post-war recovery of Ukraine

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ECOLOGICAL AND ECONOMIC ASSESSMENT OF THE EFFECTIVENESS OF IMPLEMENTING BIOENERGY TECHNOLOGIES IN THE CONDITIONS OF POST-WAR RECOVERY OF UKRAINE

Purpose. Ecological and economic assessment of the effectiveness of implementing bioenergy technologies for processing organic waste in conditions of technogenic and military risks, while also addressing the need to reduce the extraction of fossil fuels.

Methodology. The advanced global experience in bioenergy development is analyzed and considered using modern methods for calculating the technological parameters of biogas plants and determining the economic indicators of their effectiveness. The techno-economic evaluation and justification of the prospects of biogas energy are performed considering the regulatory framework and legislation of Ukraine and the European Union.

Findings. With the development of individual biogas plants, the daily output can make approximately: biogas – 370 m^3, electricity – 700 kW, thermal energy – 1100 kW. The total value of realized resources per year of operation amounts to €60,370 (of which: electricity – €31,467; thermal energy – €10,907; liquid organic fertilizers – €17,996). With investments of around €270–300 thousand and an annual profit of €21,870, the payback period of investments reaches 12–13 years.

Originality. The scientific justification for the prospect and necessity of developing biogas energy in Ukraine has been established to improve overall energy security and the eco-economic efficiency of developing low-waste technologies alongside reducing the extraction of energy resources and greenhouse gas emissions. Assuming the improvement of the regulatory framework for biogas extraction and implementation in line with EU standards, as well as grant funding from various partner countries, the payback period could be reduced from 12 to 5–6 years, which is an acceptable indicator for small private enterprises.

Practical value. The practical implementation of the proposed perspectives for the development of Ukraine's energy sector in the conditions of post-war recovery will reduce dependence on fossil fuels, increase the overall level of environmental and economic efficiency in the energy sector. The possibility of reducing the payback period of capital investments in "green energy" projects by half for farm enterprises has been justified, which positively impacts the environment and energy security of Ukraine.

Keywords: *biogas plant, economic efficiency, energy security, organic waste processing*

Introduction. The energy sector of Ukraine plays a leading role in the country's economy. Energy accounts for approximately 8 % of GDP and 25 % of taxes paid to the state budget.

In the face of economic downturn and Ukraine's commitment to the Paris Climate Agreement (a plan to limit the global surface temperature rise to 1.5 °C), over the last 30 years (1990–2020), electricity production has been halved from 298 to 154 TWh/year. This has resulted in a 67 % reduction in greenhouse gas emissions from the energy sector and combustion of fossil fuels. Despite the trend towards reduction, by 2030, this indicator needs to be further reduced by 34 % compared to existing CO_2 emissions [1].

For example, the approximate reduction in the consumption and extraction of fossil energy resources compared to 1990 to 2020 is as follows (was → became): coal 35 → 8 thousand tons (↓4.4 times); natural gas 1,546,000 → 625,000 TJ (↓2.5 times); petroleum products 42 → 10 thousand tons (↓4.2 times). Due to the significant energy intensity of production in various economic sectors, the energy sector of the country accounts for a lion's share (60 %) of greenhouse gas emissions. CO_2 emissions are mainly generated due to energy generation (thermal power plants) and transportation (Fig. 1).

Currently, due to military operations in the eastern regions of the country, the extraction of energy-related minerals is impossible. As a result, Ukraine imports mineral raw materials from EU countries, significantly increasing the cost of the final product (energy and heat supply) and facing complex logistics routes for delivery.

Significant improvement in the situation is allowed by the development of bioenergy. For example, biofuel consumption in Ukraine during the period from 1990 to 2005 was at the level of 12,000 TJ. Since 2006, there has been a trend of rapid growth to almost 84,000 TJ [1].

Strengthening the role of bioenergy is important, particularly in the context that one of the key elements of post-war recovery and economic development in Ukraine will be energy security. Due to the constant shelling and destruction of the energy infrastructure as a result of military actions, along with Ukraine's food and water security [2, 3], addressing energy security is crucial today [4]. This issue has become particularly acute for Ukraine and European countries due to their energy dependence on Russian natural gas and other mineral resources. Thus, renewable energy sources are a promising direction for energy development in developing countries [5] and in Ukraine [6]. The constant increase in the prices of energy resources and the need to develop environmental protection technologies generate significant interest in the extraction of energy from various types of organic waste for bioenergy purposes [7].

Biogas production is one of the solutions for increasing the volumes of organic waste accumulation. It also partially ad-

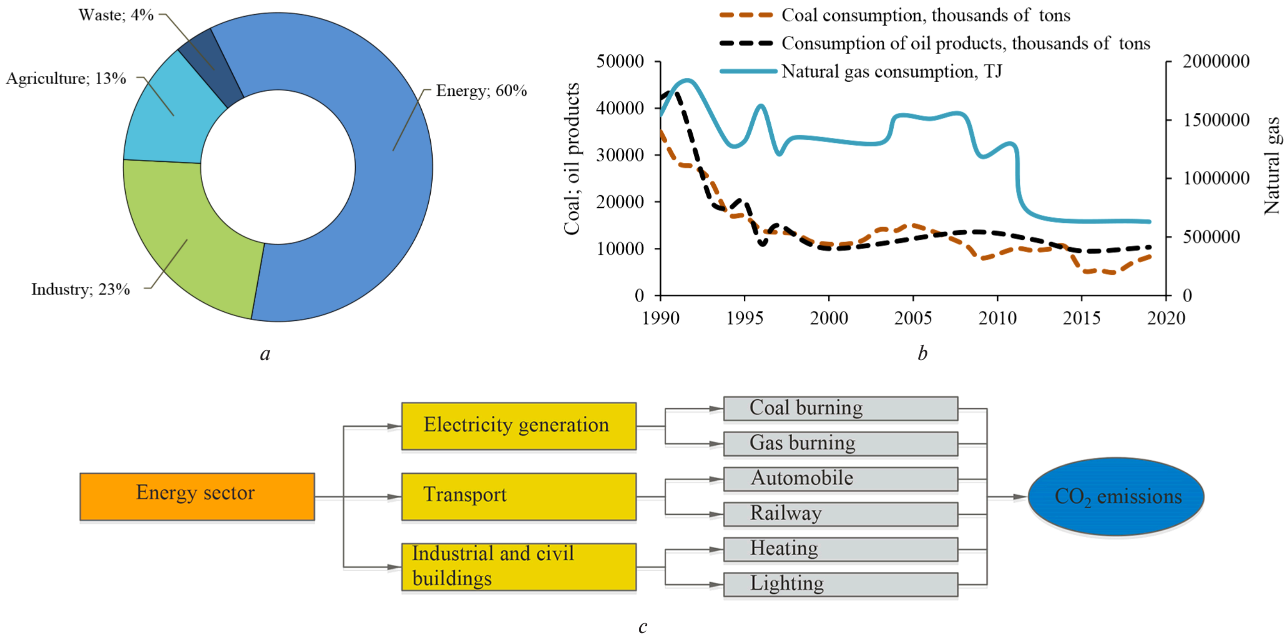

Fig. 1. Decarbonization of Ukraine's energy sector:

a – emissions of greenhouse gases by different economic sectors; b – dynamics of fossil energy consumption; c – principle of emissions formation in the energy sector

dresses the urgent need to reduce global and regional greenhouse gas emissions [8]. By converting organic waste into a renewable energy resource, biogas production opens up promising opportunities for an eco-economic chain: *continuous resource utilization → meeting the growing demand for energy services → → ensuring environmental benefits* (*safety*). Biogas can be a valuable local energy and heat source, as well as a clean fuel for cooking, reducing the dependence on the use of traditional solid biomass in many countries around the world. There are also potential associated benefits in terms of increasing food security (agriculture) and reducing the scale of mineral extraction [9].

According to leading international organizations [10], today the leaders in biogas energy development are countries of the European Union, China, and the United States (Fig. 2).

According to [11], as of 2022, there are 64 biogas plants operating in Ukraine with a total capacity of 130 MW. However, biogas production is limited to only five main types of feedstock (Fig. 3). Overall, the total potential for biomethane production (enriched biogas) in Ukraine is approximately 10 billion m^3 [12].

A distinctive feature and a promising advantage of the development of bioenergy technologies in Ukraine is the concentration of a significant amount of organic waste in the private sector and family business clusters (52–75 % of the total national structure) [13]. An analytical review shows that according to [14], economic development and the potential of bioenergy, provided that legal regulation is improved and effective state management is implemented in the direction of "green innovations", are promising for further study and implementation in production.

First, this is related to the fact that in the countries of the European Union, directives and regulations of the European Parliament [15] and various national regulatory acts are in effect, aiming to prevent the negative impact of organic waste on the components of the surrounding natural environment: *water ↔ air ↔ soil*. This requirement is best met by the processing of organic waste through methanogenic fermentation, which is fully aligned with current global trends in the pursuit of alternative sources of energy and contributes to environmental protection.

Many other studies also note a significant increase in the role of political and economic incentives for "green" innovations in EU countries after the start of the Russian-Ukrainian war [16]. The development of bioenergy remains one of the key elements for global environmental management and collective efforts to combat climate change.

The aim of the research is to provide an ecological-economic assessment of the effectiveness of implementing biogas processing technologies for organic waste, which justifies the representativeness of the research for Ukraine. The work is done taking into account the existing regulatory framework for this issue in Ukraine and the prospects for its approximation and implementation of EU standards in the conditions of

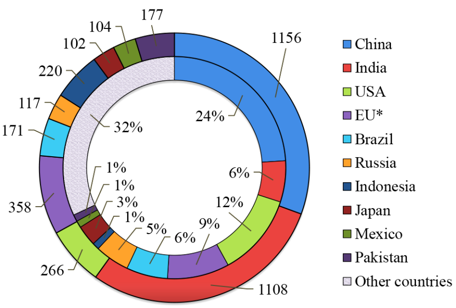

Fig. 2. Top 10 priority countries for biogas production: approximate biogas potential (*TWh*)*; share* (*%*) *of global greenhouse gas emissions; *EU includes 28 countries* (*including UK*)

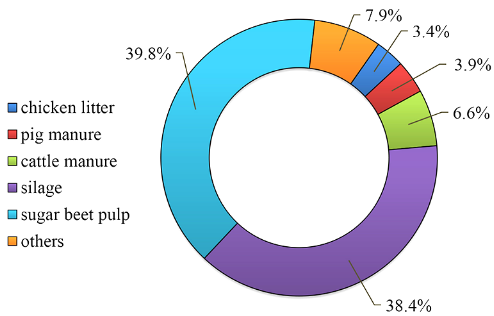

Fig. 3. Structure of the raw materials used for the production of biogas in Ukraine

post-war recovery of Ukraine in order to increase the country's energy security.

Materials and methods. Biogas installation is proposed for the processing of organic waste, with the arrangement according to Fig. 4. Such arrangement allows obtaining biogas and fermented substrate, which is a liquid organic fertilizer. Biogas, in turn, is a source of energy for a cogeneration unit, through which electricity and hot water (thermal energy) can be obtained.

The amount of organic substrate that can be used in the biogas installation depends on various technological features and the process of its obtaining, storage, and preparation [17]. According to existing experience, the moisture content of such organic waste is 92–96 %, with a density of 1,005–1,030 kg/m^3.

To achieve the research goal, it is necessary to determine the investment size in the project, operational expenses for the operation of the biogas plant, the amount of biogas and electricity that can be obtained with its help. The income from the operation of the biogas plant will be generated from the sale of electricity at the "green" tariff [18]: (0.123 €/kWh), thermal energy (0.027 €/kWh), and liquid organic fertilizer (4.81 €/ton). The indicators of the economic efficiency of the plant operation were calculated using recommendations [19].

Results and discussion. In accordance with [20], the average investment cost of a biogas plant with an electrical capacity of up to 75 kW is 9,000 €/kW. In this case, the reduction of expenses for small biogas plants can be reduced to 5,500 €/kW through the construction part of the project, namely the methane tank with a gas holder and the input receiver of the raw material. Under these conditions, it is possible to use technological equipment that has a lower purchase cost.

The volume of the methane tank (bioreactor), and therefore, the construction cost will depend on the duration of fermentation, which in turn depends on the temperature regime. The most common ones today are the following [21]: psychrophilic (20–25 °C) lasting 30–40 days, mesophilic (32–42 °C) – 20–30 days, and thermophilic (50–57 °C) – 10–15 days respectively. Thus, the highest construction costs will be under the conditions of using a psychrophilic regime, and the lowest – with a thermophilic one; however, the latter requires higher expenses to maintain the required temperature level and is the most sensitive to its fluctuations [22].

The amount of biogas obtained is determined taking into account the data [23]. From one kilogram of organic waste dry matter, up to 0.45 m^3 of biogas can be obtained.

Electric and thermal energy will be produced using a cogeneration plant, which includes a specialized internal combustion engine and an electric generator. From the technical characteristics of cogenerators, it is determined that 1 m^3 of biogas can yield 1.8–2.3 kW of electrical and 2.9–3.2 kW of thermal energy (lower values for smaller capacity installations).

Taking into account the above data, the technological parameters of the biogas plant operation will be as follows (Table 1).

According to the calculations received, the electric power of the biogas plant will be 29 kW, and taking into account the capital investment data mentioned above (9,000 €/kW), the approximate investment amount for the implementation of such a project will be 262.8 thousand €. Operational expenses will include costs for energy resources (electricity and thermal energy for heating the methane tank), personnel salaries, maintenance, repairs, and other operational expenses. Based on existing experience [24], annual operational expenses constitute approximately 14.6 % of the total structure. Thus, for our conditions, operational expenses will amount to approximately €38.5 thousand. The results of the technical and economic evaluation of the biogas plant operation are presented in Table 2.

Based on the results of the economic calculations obtained, it has been established that the payback period of the investments exceeds 12 years, which, of course, is not an attractive indicator for potential investors. Analyzing the income component, the total value of the realized electricity constitutes more than 50 % of the total – €31,466.67; heat energy obtained – 18 %; liquid organic fertilizers – 30 %. As for the latter, this is a European experience, which is controversial in the current conditions for Ukraine, where there is practically no regulatory framework for organic waste [25]. However, this direction can be promising in terms of obtaining organic environmentally friendly products, which also have higher economic efficiency in sales compared to other types of products. The efficiency indicators can be slightly improved by referring to the resolution of the National Commission for State Regulation in the Spheres of Energy and Utilities (NCSREU) [18]. This document indicates that when using equipment of Ukrainian production, an additional charge of €0.012 is provided for the "green" tariff, which means that the cost of electricity during implementation will be 0.135 €/kWh. In this case, the payback period will slightly improve and amount to 10.4 years. If the "green" tariff is used, as applied, for example, in Germany

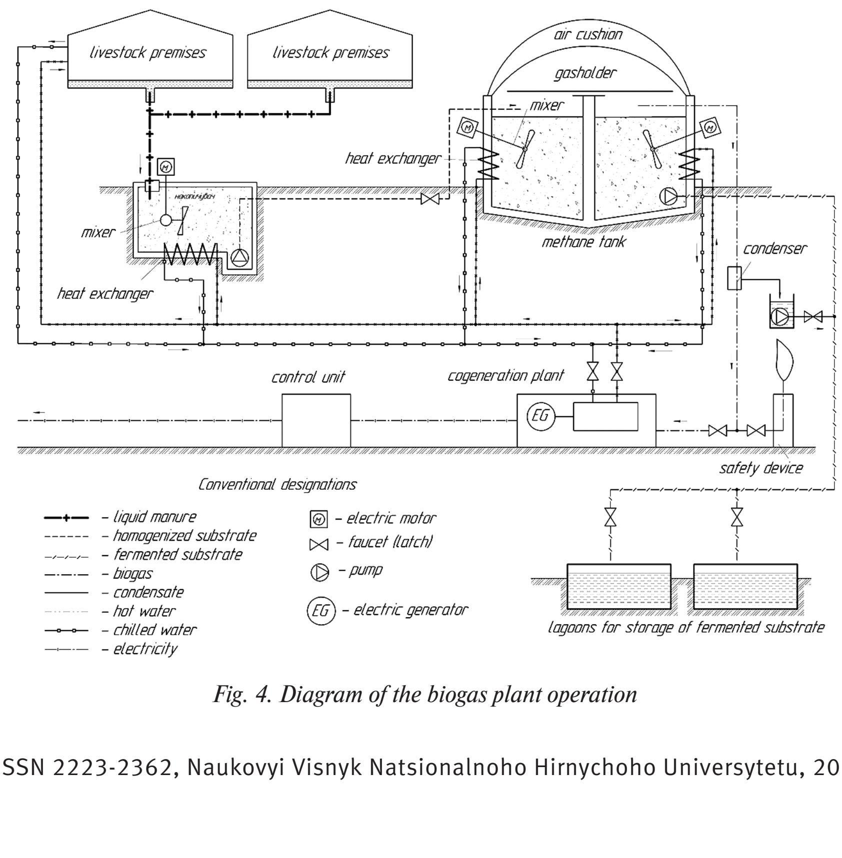

Fig. 4. Diagram of the biogas plant operation

Table 1

Technological parameters of biogas plant operation

Indicator	Value
Daily load of substrate, kg	10,247.0
Dry matter content at a humidity of 92 %, kg	819.7
Biogas output from 1 kg of dry matter, m^3/h	0.45
Biogas output, m^3/h	15.4
Electricity output, kW/h	29.2
Thermal energy output, kW/h	46.1
Daily output of biogas, m^3	368.9
Daily electricity output, kW	700.9
Daily heat energy output, kW	1,106.7

Table 2

Technical and economic indicators of the studied biogas plant

Indicator	Value
Annual output of electricity, kW	255,826.6
Cost of electricity at sale, €/kW	0.123
Total cost of sold electricity, €	31,466.7
Annual output of thermal energy, kW	403,936.7
The cost of thermal energy during implementation, €/kW	0.027
Total cost of realized thermal energy, €	10,906.3
Annual output of liquid organic fertilizers, i.e.	3,740.2
Cost of liquid organic fertilizers at sale, €/t	4.81
The total cost of liquid organic fertilizers at sale, €	17,995.38
Total cost of realized resources, €	60,368.35
Investments, €	262,800.0
Operating expenses, €	38,500.0
Profit, €	21,868.4
Investment payback period, years	12.02

for small (up to 75 kWh of electricity) biogas plants – €0.23, then we will get a payback period of 5.34 years. This situation justifies the need to revise the regulatory framework and its improvement to EU standards, which will contribute to further active development of bioenergy.

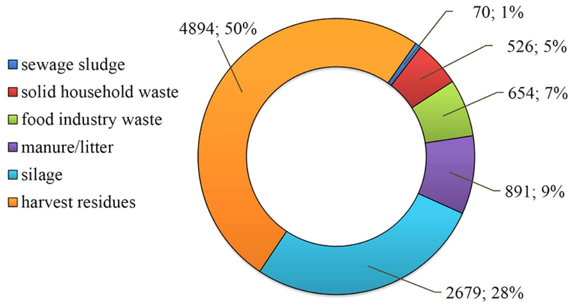

Fig. 5. General structure of biogas production potential in Ukraine (mln. m^3; %)

In addition to the discussed option of operating a biogas plant, various organic waste can potentially be used as raw materials (Fig. 5).

It is worth noting that during peacetime, the development of the Ukrainian energy sector also involved several initiatives aimed at reducing CO_2 emissions. The baseline scenario for development was based on the necessity of certain changes (Fig. 6). Based on the conceptual principles of Ukraine's energy development and current conditions, several conclusions can be drawn. Due to military actions and constant missile attacks on the energy infrastructure, the implementation of measures related to the preservation and modernization of existing thermal power plants and combined heat and power plants can be a significant challenge. The destruction of the Kakhovka Hydroelectric Power Plant [26] also poses several difficulties in the operation of hydroelectric power, which played a crucial role in regulating peak loads (energy system deficit) during specific daily time intervals. Ensuring the reliability and radiation safety of further operation of the Zaporizhzhia Nuclear Power Plant at regional and transboundary levels is an essential and vital element of environmental policy. The limited and complex extraction of coal, oil, and gas in the eastern regions of the country necessitates prioritizing the exploration of alternative energy sources, taking into account advanced global experience and internal eco-economic potential for reducing greenhouse gas emissions.

The obtained research results and the consideration of various types of stimulation (economic, political and environmental) are consistent with the findings of previous studies by other authors [14, 27]. For the conditions in Ukraine, we can emphasize that the development of bioenergy is possible through the adoption of "foreign" indicators of environmental policy stringency. There are enough examples around the world of replacing traditional fossil fuel energy sources with

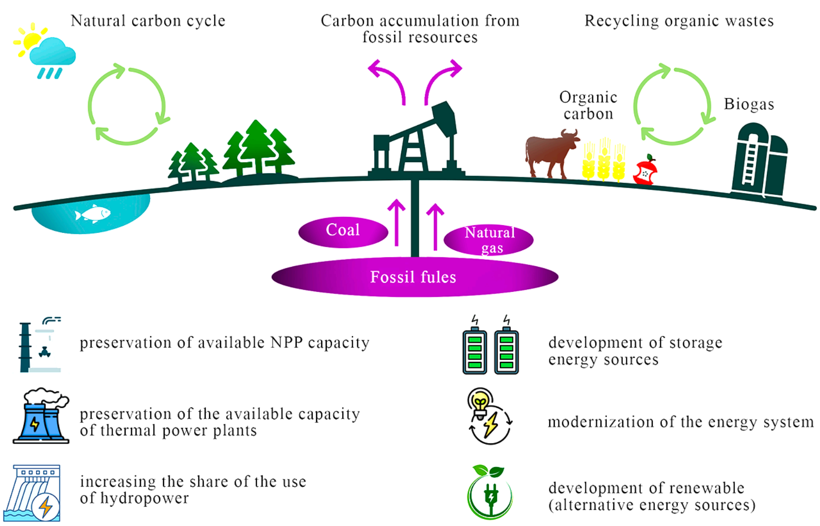

Fig. 6. Basic scenarios of energy sector development considering greenhouse gas emissions reduction

the practical application of knowledge and technologies in the field of bioenergy. We believe that the key to their implementation today remains to adhere to the sequence of political decisions and to improve the regulatory framework for developing countries.

Stimulating clean energy technologies, which are central to global efforts to limit CO_2 emissions and climate change, could allow Ukraine to accelerate the implementation and adoption of more standards on the path to EU membership.

Approximately 20 % of the stimulating projects in EU countries in recent years have been specifically dedicated to bioelectricity (mostly biogas and new biomass production facilities) [16]. However, as before, the dominant support schemes for the implementation of bioelectricity are green tariffs and preferential surcharges, while subsidies remain the main state support for obtaining bioheat. Furthermore, the vast majority of EU countries apply mandatory mixing quotas for biofuels with traditional fuels for transport. Thus, biomass for energy continues to play a key role in the EU policy on supporting renewable energy sources. It should be noted that further harmonization of state support for bioenergy with the EU single market for environmentally friendly energy is recommended in studies [16]. This involves four policy actions for all EU member states: in-depth efficiency analysis, integration, joint guiding principles of sustainable development, and assessments of local impact (environmental protection), which are undoubtedly relevant for further research.

Thus, the implementation of small biogas plants in Ukraine in the conditions of post-war recovery can be promising provided that domestic legislation is adapted to EU regulations on regulating the handling of organic waste and pricing "green" energy.

Conclusions. Converting organic waste into biogas is a global trend that provides an alternative source of energy, helps reduce the extraction of energy resources, and contributes to environmental protection.

In the conditions of post-war recovery in Ukraine, one of the promising directions is the utilization of various organic waste from private sector production as a substrate in biogas energy production, as part of the overall potential to obtain around 10 billion cubic meters of biomethane.

Under the current legislative framework, the techno-economic assessment of a biogas plant project has shown low investment attractiveness with a payback period of more than 10 years. However, the adoption of best practices and examples from the EU in regulatory aspects in this area demonstrates the relevance of such solutions, allowing the payback period of similar projects in Ukraine to be reduced to 5–6 years.

The establishment of a biogas plant with the involvement of foreign investments and participation in grant projects for financing is promising for the development of family businesses and small agricultural enterprises.

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Еколого-економічна оцінка ефективності впровадження біоенергетичних технологій в умовах повоєнного відновлення України

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Мета. Еколого-економічна оцінка ефективності впровадження біоенергетичних технологій переробки органічних відходів в умовах техногенних і військових ризиків і необхідності зменшення видобутку викопних корисних копалин.

Методика. Проаналізовано та враховано передовий світовий досвід розвитку біоенергетики з використанням сучасних методів розрахунку технологічних параметрів роботи біогазової установки й визначення економічних показників її ефективності. Техніко-економічне оцінювання та обґрунтування перспективності біогазової енергетики виконане з урахуванням нормативно-правової бази й законодавства України та Європейського Союзу.

Результати. За умов розвитку індивідуальних біогазових установок добовий вихід може складати близько: біогазу 370 м^3, електроенергії 700 кВт, теплової енергії 1100 кВт. При цьому загальна вартість реалізованих ресурсів за один рік експлуатації становить 60 370 € (з яких: електроенергії – 31 467 €; теплової енергії – 10 907 €; рідких органічних добрив – 17 996 €). При капіталовкладеннях у близько 270–300 тис.€ та щорічного прибутку 21 870 €, термін окупності інвестицій сягає 12–13 років.

Наукова новизна. Науково обґрунтована перспективність і необхідність розвитку біогазової енергетики в Україні задля підвищення загального рівня енергетичної безпеки та еколого-економічної ефективності розвитку маловідходних технологій наряду зі зменшенням обсягів видобутку енергетичних корисних копалин і викидів парникових газів. За умови удосконалення нормативно-правової бази з видобутку й реалізації біогазової енергії до нормативів ЄС, а також грантового фінансування галузі різними країнами-партнерами, термін окупності може бути скорочений з 12 до 5–6 років, що є прийнятним показником для невеликих приватних підприємств.

Практична значимість. Практична реалізація запропонованих перспективних варіантів розвитку енергетичного сектору України в умовах повоєнного відновлення дозволить знизити енергозалежність від викопних корисних копалин, підвищити загальний рівень екологічної та економічної ефективності роботи енергетичного сектору. Обґрунтована можливість зменшення терміну окупності капітальних вкладень у проєктах «зеленої енергетики» вдвічі для умов фермерських господарств, що позитивно впливає на навколишнє середовище та енергетичну безпеку України.

Ключові слова: *біогазова установка, економічна ефективність, енергетична безпека, переробка органічних відходів*

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